Partners for Innovation

FIRST DRAFT OF CASE STUDY 1.2: BISCUIT PACKAGING

An example of weighing sustainability criteria for plastic flexible food packaging

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TABLE OF CONTENTS

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1. INTRODUCTION

Global plastics production has reached 311 million metric tons and is expected to continue to grow by around 4% annually for the foreseeable future. While plastics deliver many benefits to society, there is an increasing awareness of the potential impact of chemical components of plastics on human health and the environment.

The Organisation for Economic Co-operation and Development (OECD) organised a Global Forum on Environment focussed on "Plastics in a Circular Economy: Design of Sustainable Plastics from a Chemicals Perspective" in 2018. The Forum sought to incentivise a shift in sustainable chemistry thinking at the product design stage by identifying good practices, including tools and approaches, as well as a policy framework to reduce the environmental and health plastics impacts. This resulted in multiple reports on the sustainability of plastics from a chemical perspective.

To build on this research and translate it to practical insights for packaging designers the OECD Global Forum for the Environment commissioned the development of this case study on sustainability consideration on a chemical level for plastic design for plastic film for biscuit packaging. In this case study a lifecycle approach is taken for the development of plastics packaging film for biscuits. All sustainability aspects regarding human health and the environment are considered, resulting in sustainability considerations on sustainability for people throughout the value chain who are involved in the design of the plastic packaging film. This enables sustainable designs tailored to the specific life cycle scenario of a packaging film for biscuits.

Another case study that is developed regards the sustainable design of plastics detergent bottles. The two case studies conducted are intended to set an example for other sectors and product categories.

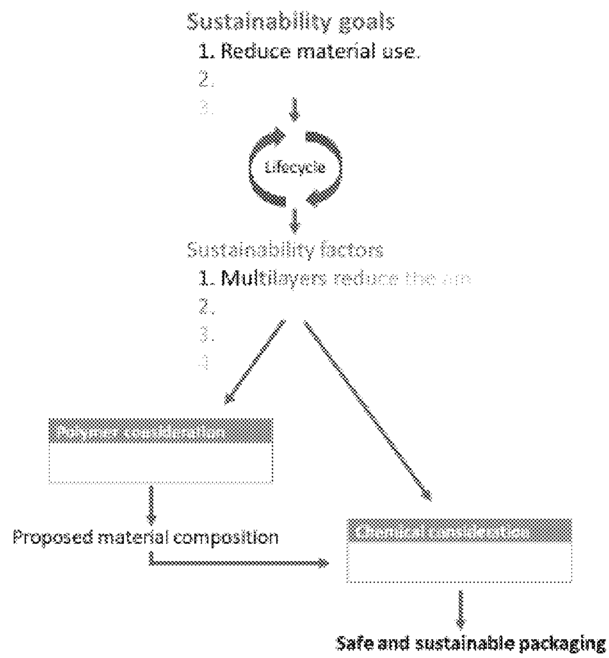
1.1 READING GUIDE

Lifecycle approach

The sustainability aspects are assessed for the life cycle stages through which a plastic packaging film cycles: sourcing of the material, production and filling of the packaging, use of the packaging to store the biscuits and consumption of the biscuits, and end of use at which the plastic film is discarded and processed. At each stage in the life cycle different considerations regarding sustainability come into play, while decisions in one stage might also affect the impact at other stages. From a designers' perspective this journey will start with the use phase. The purpose of the product and the context in which it will be used, determine the basic set of technical requirements and constraints for a shortlist of possible materials. Therefore this case study will consider the use phase first, after which the sourcing of the feedstock, the production of bottles and its end-of-use are discussed.

Case study structure

In the subsequent chapters the different life cycle stages will be discussed. Per chapter a general overview of the life cycle stage is provided, describing the different processes and relevant factors that influence sustainability of the packaging. The relevant sustainability factors are identified by keeping a list of Sustainable Design Goals in mind while working through the life cycle stages. Each sustainability factor leads to a polymer or chemical consideration; a decision that needs to be made to select a polymer or a chemical in the production of the plastic packaging film. Some of these considerations are on a higher detail level: the selection of a polymer or the combination of materials in the film. These are key considerations and need to be addressed first in the plastic selection process. Other considerations are on a much more detailed level: once a polymer or a group of materials has been chosen to form the packaging, the chemical additives that used in production of the film need to be selected. These are chemical considerations, they are listed when the life cycle is analysed and an example for each is given.



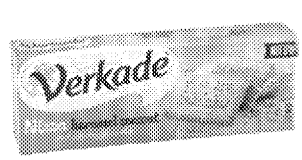
Once all aspects of the life cycle have been considered, an overview of Key Considerations and Trade-offs is provided in Chapter 7. Subsequently, the key considerations regarding the polymer choice will be simultaneously assessed in an example of a choice matrix in chapter 8. An overview of the chemical considerations that follow after the polymer selection is also given. This is a reminder for further investigation into details that cannot all be considered in one step.

1.2 SCOPE

In the case study it is assumed that the choice for a flexible plastic packaging has been made and now the most sustainable option needs to be found. Alternative materials and forms of packaging such as metal containers or cardboard boxes are not taken into account because they will allow for an almost unlimited range of comparisons and considerations.

Description of the packaging film

A flexible plastic packaging for biscuits, or a 'wrapper', consists of thin plastic film. Cookies are collated in a stack, in a plastic tray, a corrugated cardboard sleeve, or are individually packed. The film can have the shape of a tube that is closed at either sides of the product with a heat seal or the film is wrapped around the biscuits and folded and sealed shut.



For commercial reasons, the packaging is usually very colourful with images and product information directly printed on the packaging film. The use of additional labels or stickers is rare. The plastic film itself is generally a combination of materials, both plastics and non-plastics, to meet requirements like barrier properties, strength, printability, and sealing.

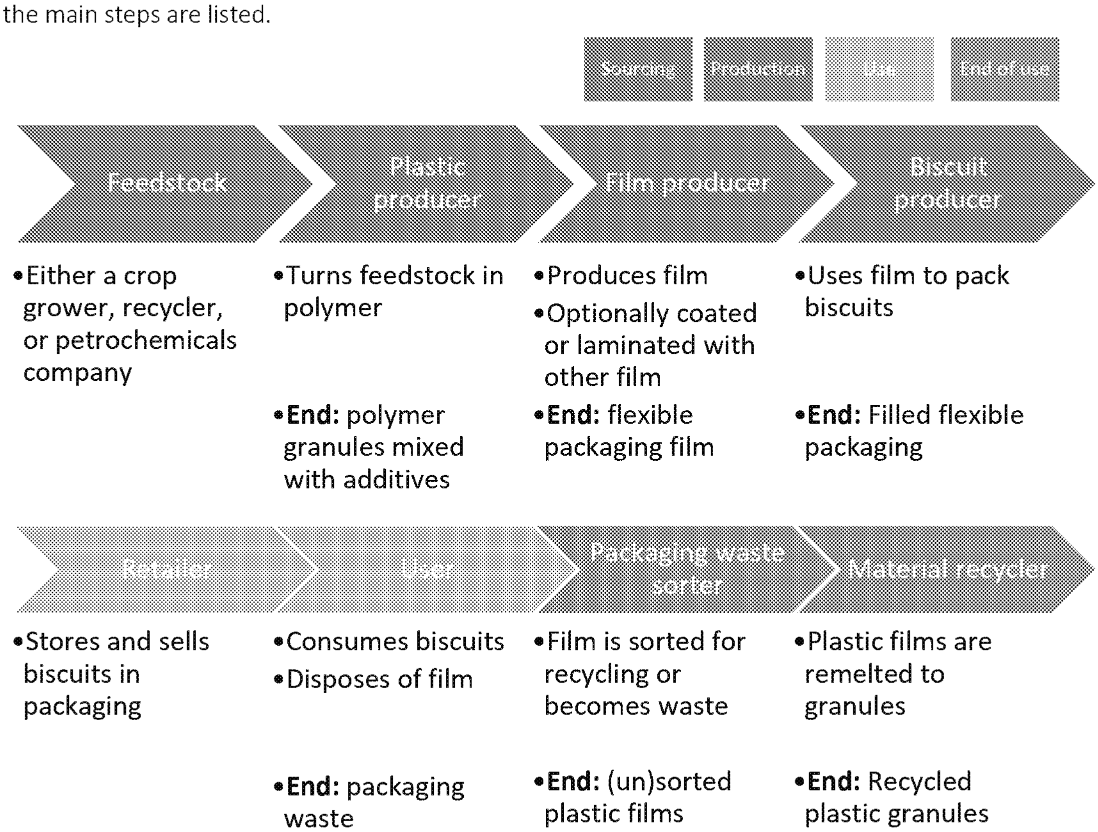
Requirements to packaging

The overarching requirements set to all these different forms of flexible plastic packaging for biscuits are:

- Display the biscuits in an attractive way at the point of sale
- Display the information about the ingredients and the manufacturer of the biscuits
- Maintain the taste, crispness, and smell of the biscuit
- Make the biscuits easy to stack in transport and storage
- Protect the biscuits from breaking during transportation

1.3 OVERVIEW OF THE LIFECYCLE

In the lifecycle of the plastic packaging film for biscuits will be discussed divided in four stages: Sourcing, Production, Use, and End of Use. In the visual overview below, the stages are shown and the main steps are listed.



1.4 SUSTAINABLE DESIGN GOALS

The following five sustainable design goals are chosen for the case study of a plastic biscuit packaging. Examples of other goals are given at the end of the section.

Prevent product spoilage

The packaging serves to protect the product. Usually the (environmental) impact of the product's production is far greater than that of the packaging's total lifecycle. Preventing the waste of the product before it reaches its intended goal is an important goal in the sustainable design of the packaging.

Reduce material use

Packaging is a short-lived product but amounts to 40% of the world's total use of plastic. Designers should strive to reduce the use of plastic to the absolute minimum to perform the packaging duties.

Close material loops

Due to the short-lived use of packaging, the used material should make multiple lifecycles. The plastic should either be made from secondary feedstock or be able to be used a second time in another product. In an ideal situation a combination of both is made.

Preserve natural capital

Humans depend on natural capital for a wide range of ecosystem services. Poorly managed natural capital can destroy productivity and resilience, making it difficult for humans and other species to sustain themselves. Destruction of natural capital throughout the packaging lifecycle can occur in the form of land use for mining and crop growing, biodiversity loss due to toxic emissions, exhaustion of feedstock, and climate impact through to greenhouse gas emissions.

Guard health of participants in lifecycle

From feedstock extraction, through packaging manufacturing and product use, to the eventual end-of-Use scenario, the packaging and its subcomponents will interact with humans. The direct negative effects of the packaging and its subcomponents on the health of these people needs to minimized. The focus in this case study will be in two phases of the life cycle. The first are the health risks for consumers in the use phase through contamination of the food or through skin contact with the packaging. The second are the risks for recycling facility employees who get into contact with the chemicals during treatment of the packaging waste and risks for the general population when chemicals spread into the environment due to waste treatment. It is assumed that the health risks at the plastic producing plants, film manufacturers, and product packaging facilities are known and adequate precautions are taken. This is not the case for individual consumers or waste management employees.

Examples of other sustainable design goals

The five goals listed above are chosen for this case study. Other sustainable design goals might be:

- Minimize waste
- Improve social conditions throughout the life cycle
- Decouple from fossil resources

1.5 DECISION MAKING PROCESS

During the design process the listed five sustainable design goals will be considered to select the most sustainable plastic(s) to be used in the packaging. During the analysis of the lifecycle it will show that trade-offs will need to be made. The decision for one material based on one goal in one phase of the lifecycle will counteract the realisation of another goal in another part of the lifecycle. Besides the selection of a polymer for the packaging, the use of chemicals in the production of the polymer and the packaging and their consequences in later stages of the lifecycle must be considered. Especially since the packaging is used for food stuff, the migration of possibly hazardous substance to the biscuits must be taken into account.

Selecting a polymer, or combination of polymers, for the packaging film results in a list of options and a few important considerations and trade-offs. Taking all possible chemical additives and residual by-products into account for the list of considered polymers, results in a number of criteria that cannot all together be considered.

To be able to make the best overall decision the Hybrid Decision Methodology will be used.

Based on the overarching five sustainable design goals, sub-criteria will be identified throughout the lifecycle. The criteria will be listed and weighted; some will be regarded as key considerations while others will have a minor roll on the overall sustainability of the packaging. Data on the optional polymers for the plastic film and the additives will be collected. Then, all the polymers will be compared to the selected key considerations. The polymer that is identified as the best fit (i.e. with the lowest impact on environmental sustainability and human health) will preliminary be selected for the biscuit packaging.

Subsequently, for the selected polymer only, will relevant chemical additives be investigated on their food safety and environmental consequences. Alternatives might need to be found for unsustainable chemicals. Or when this specific substance is inevitable, the importance of the corresponding sustainability factor needs to be considered. If the factor is important and no sustainable alternative for the chemical is found, another polymer needs to be selected. In chapter 2 food safety and existing regulation on chemical use in plastics and for food applications specific will be discussed. In section 2.3 the incorporation of safe chemical selection will be discussed in further detail.

2. FOOD SAFETY AND CHEMICALS REGULATION

2.1 REGULATIONS ON CHEMICALS IN PLASTICS

Multiple national and international food safety authorities have their own lists of substances that are prohibited in food applications or are limited in use.

EU: REACH

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is a regulation from the European Union to control the health and environmental risks of chemicals. It restricts the use of chemicals with known risks, obliges producers to communicate about the risks, and forces producers to register new chemicals and evaluate their risk to the environment and human health. Based on the hazard categories (discussed in paragraph 2.5) and the hazard level, substances are either banned or restricted in use.

EU: Commission Regulation (EU) No 10/2011

A regulation on plastic materials and articles intended to come into contact with food, with the *Union list of authorised substances.* A 'positive list' of substances that can be used in the production of plastics that come in contact with food and the specific migration limits for these substances. It further requires and details compliance testing of materials and the requires each manufacturer in the supply chain to provide a declaration of compliance. This means that both the finished packaging and intermediate products need to comply to their own obligations. For the producer of the plastic resin or chemical additive this means that authorised substances are used, for the manufacturer of the packaging it means that migration testing are performed and passed.

[More relevant regulation for other OECD regions will be added.]

Restricted Substances List of the Cradle to Cradle Products Innovation Institute

The Cradle to Cradle Products Innovation Institute is not a regulatory body that can restrict the use of substances in products in a given market. It is a non-profit organization that maintains a standard for products and materials to become 'Cradle to Cradle certified'. This is a certification for sustainable products and certifies them as safe, responsible, and fit for a circular economy. The Restricted Substances List (RSL) is a checklist for materials that cannot be used in certified products. The list is comprised of restrictions on chemicals from multiple existing chemical regulations such as the one mentioned above. The most conservative thresholds for each substance in any of the combined regulations is chosen. The fourth version of the RSL is expected in January 2021 and will be updated annually.

2.2 HAZARD CATEGORIES

In this paragraph the main hazard categories for human health will be discussed. To these categories will be referred when discussing chemicals in the lifecycle phases. The chemicals can pose risks in all lifecycle phases: to a consumer when he interacts with the packaging or eats food from the packaging, but also to a plant operator in the production of the packaging, or to recycling facility staff or life in the nearby environment at the End of Use phase. These categories are the ones defined under the EU's REACH regulation.

CMR

This category contains substances that are

- Carcinogenic: causes cancer growth
- Mutagenic: alters genetic material or increases mutations
- Reprotoxic: causes infertility or reduces development of offspring

PBT and vPvB

Two other categories defined in REACH regulation. PBT are substances that are:

- Persistent: do not degrade or degrade very slowly in the environment or in organisms
- Bioaccumulative: accumulate in organisms faster than they are excreted or degraded
- Toxic: causes harm when inhaled, ingested, absorbed, or touched

vPvB stands for very Persistent or very Bioaccumulative.

Endocrine disrupting chemicals (EDC)

Substances that interfere with the regular functioning of hormones and hormone receptors

Chemical substances can be classified as part of multiple hazard categories. Bioaccumulative substances might lead to reprotoxic consequences, endocrine disruption might lead to cancer growth and fertility is dependent on well-functioning hormones.

2.3 INCORPORATION OF SAFE CHEMICAL SELECTION IN THE DESIGN PROCESS

With this document the following method for selection of chemicals for plastic food packaging film is proposed:

1. Demand from all your suppliers that they adhere to the local regulations on food contact materials.
2. Use a lifecycle approach to map out the relevant considerations concerning chemicals and their effects throughout all lifecycle stages.
3. Select a material or material combination for the packaging according to the Decision-making process, explained in section 1.5.
4. Check, in collaboration with your material supplier if necessary, whether the found chemical considerations involve any of the substances on the Restricted Substances List (RSL) of the Cradle to Cradle Products Innovation Institute.
5. If substances on the RSL are part of a chemical consideration, try to find an alternative substance for the intended goal.
6. If no alternative is possible, verify that the concentration of the substance is below the limit set in the RSL.
7. If incorporation of substances on the RSL is inevitable for the product, verify through relevant migration tests that these substances do not migrate into the food at all.
8. If steps 6 or 7 cannot be passed, revisit step 3 and select another material or material combination.

3. USE PHASE

3.1 INTRODUCTION

In the use phase the packaging is used for its intended goal: getting the biscuits from the producer to the consumer safely, providing information, and attracting attention in the shop. In this phase it touches upon three of the five overarching sustainability goals: (1) preserving the biscuits, (2) while using as little material as possible, and (3) without exposing humans to hazardous chemicals in the packaging.

The biscuits are a food that is going to be digested by the consumer. The plastic that is in contact with the food should not release chemicals in hazardous amounts to the biscuits or harm consumers in other ways, such as through skin contact. Nor should the material or some of its constituents change the food composition, taste, or odour in an unacceptable way.

Packaging is used to convey information about the biscuits to the consumer and advertise the product at the point of sale. Text and full colour images are printed on the packaging to do so. The printing is done in the production phase of the packaging but discussed in this chapter because this is where it serves its purpose.

3.2 BARRIER PROPERTIES - PREVENT PRODUCT SPOILAGE

Functions of the plastic biscuit packaging are collating the individual cookies, labelling and advertising, and mechanical protection (i.e. prevent breaking). However, these functions can be performed by packaging made from other materials. The plastic packaging is usually chosen because it serves to protect the biscuits from deterioration. The quality of the biscuits can be spoiled in several ways. Moisture uptake will make the biscuits lose their crunch. Oxidation of fats in the biscuit will change the taste, or uptake of odours from the environment will change the taste and smell of the cookies.

Based on interviews with a number of packaging producers and European biscuit producers, there are three main requirements for biscuit film packaging.

The Water Vapor barrier of the plastic to prevent moisture uptake. Biscuits are expected to be crisp and the crunch is the easiest lost in the journey between production and the consumer.

Tear resistance of the film is an important factor since the barriers will only last as long as the packaging is intact. As mentioned under *General Analysis*, a thin plastic film is used to minimize the amount of material used in the packaging. The further the thickness of the film is reduced, the greater the chance of damage to the packaging. A thin film with good barrier properties but low tear resistance will not survive the logistics channel of the biscuits from producer to consumer.

Heat sealing of the film on a fast filling line. On the fast paced, high volume packaging lines a plastic film is wrapped around the biscuits in a bag. In both cases the packaging needs to be closed and this commonly done through heat sealing. This will be discussed in further detail in the *Production* chapter.

	Vapor barrier	Oxygen barrier	Tear resistance	Heat sealing
LDPE	Moderate	Bad	Moderate	Good
HDPE	Good	Bad	Good	Good
PP	Moderate	Bad	Good	Good
BOPP	Good	Bad	Excellent	Bad
PET	Moderate	Moderate	Excellent	Bad
BOPET	Moderate	Good	Excellent	Bad
PA	Bad	Good	Excellent	Bad
PLA	Bad	Bad	Bad	Moderate
Regenerated cellulose	Bad	Good	Good	Bad
coatings				
Acrylics	Bad	Bad	Bad	Good
PVdC	Excellent	Excellent	Bad	Bad
PVOH	Bad	Excellent	Bad	Good
EVOH	Bad	Excellent	Bad	Moderate
EVA	Bad	Bad	Good	Good

Ranking order: bad-moderate-good-excellent. Based on CEFLEX (2020), KIDV (2019), Dixon (2001), and Polymerdatabase (2020)

[The content of this table is under review.]

Polymer consideration
In this phase the barrier properties, strength, and ease of sealing of the polymers are to be considered for the main polymer selection. The barrier properties and tear resistance are derived from the goal to prevent product spoilage, the ease of heat sealing is required in an efficient packaging process and is a typical constraint for this specific application.

Multilayer films

To improve the properties of the packaging film, multiple layers of polymers can be combined. A thin layer of a polymer with a good oxygen barrier can be combined with a thin layer of a polymer with a good vapor barrier. This can drastically reduce the amount of (mono-)material required to perform both functions. However, these multilayers do have their consequences in other phases of the packaging's life cycle. This will be discussed in further detail in the Chapters *Production* and *End of Use*.

Metalized film and paper composites

While aluminium and paper are not a plastic, it is included in this paragraph because they are both used in combination with polymers in the application of biscuit packaging.

Non-plastics	Vapor barrier	Oxygen barrier	Tear resistance	Heat sealing
Aluminium foil	Absolute	Absolute	Bad	Bad
Aluminium oxide	Excellent	Excellent	Bad	Bad
Paper	Bad	Bad	Good	Bad

These non-plastic materials are left out of scope for the remainder of this case study. Sustainability considerations that can be taken into account are that the potential for recycling and biodegradability decreases when materials are combined, that these materials require responsible sourcing, and will also need to adhere to food safety regulations.

Design consideration
A consideration that is not on a chemical level but has great impact on the overall sustainability and the amount of chemical considerations that will follow is: Should multiple layers of different polymers or even other materials be used? • With a combination of materials, the packaging can both have the desired properties and reduce the amount of material required. Using a smaller amount of material will reduce the environmental burden in sourcing and production and decrease the eventual wasted material. Furthermore, the reduction of material will reduce the absolute amount of potentially harmful chemicals in the plastic and consequently decrease their migration into food and release into the surroundings during production or at end of use. • However, a combination of materials will increase the complexity of the packaging and reduce the potential for recycling or biodegradation at end of use. A combination of materials will require extra production steps and the use of substances such as adhesives and compatibilizers. Using multiple materials will multiply the uncertainties about non-identified chemicals in the packaging and their effects on the food safety and their undesired degradation effects at end of use.

3.3 CONSUMERS GET IN CONTACT WITH CHEMICALS IN THE PLASTIC

In this phase the health risks for the consumer need to be considered. What are known health risks associated with the polymers and their chemical constituents? Both migration of chemicals into the food and skin contact need to be considered. The important hazard categories have been discussed in section 2.2, these can be linked to chemicals that occur in the packaging. These chemicals will be added in the production of the plastic and the subsequent production of the film from the plastic.

The incorporation of these substances in the film will be discussed in the lifecycle phase where they serve there purpose. For instance, the risks and impact of printing inks are considered in this chapter because they are added to the packaging to convey information to the consumer or to seduce the consumer at the point of sale. Some chemicals might be left in the plastic that aided in the polymerisation process, these are discussed in the Sourcing chapter, while release coatings used in the packaging production are described in the Production chapter.

3.4 PRINTING AND INKS

Biscuits are sold in attractive packaging to seduce consumers, with images and colours printed on transparent or evenly white coloured films. Food producers are required to print information about ingredients and nutritional value on the packaging. The inks that are used and their chemical constituents can have great on the overall sustainability. No hazardous substances from the ink should contaminate the consumers hands during use or contaminate the biscuits. Depending on the quantities and substances used, inks can have negative effects when leached into the environment in a landfill, cause issues in recycling, and carry both environmental and health risks when burned.

Printing techniques

There are multiple methods to apply ink on a surface. Flexographic printing, gravure printing, inkjet printing, and more. There are differences with respect to sustainability between these methods, but in the chemical selection for a flexible food packaging two other aspects are of much greater importance: the surface on which is printed and the curing of the inks on the printed surface.

Plastic films can either be surface printed, on the outside of the plastic film, or reverse printed, on the inside of one layer that is then laminated on a second layer of film.

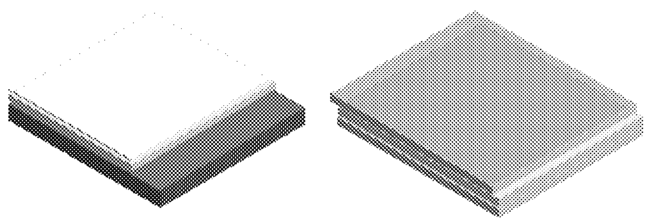


Figure 4: A depiction of a surface printed plastic film with overcoating (L) and laminated film with reverse printing in between (R).

Surface printed inks have as downside that they can be rubbed off a contaminate the fingers of the consumer or form miniscule airborne particles that enter the respiratory system. In the production process films are stacked as sheets or rolled as one piece on a reel. Surface printed inks on the outside can set-off to the food contact layer on the other side. To prevent this, overprint coatings can be applied. This is a thin printed layer that with the same composition as the ink, but without pigments (Mieth, Hoekstra & Simoneau, 2016).

Reverse printed inks are usually applied to the outer most plastic layer when multilayer films are used. It protects the inks from rubbing of and prevents direct migration to the food or skin. However, it does require the lamination of multiple plastic layers in the film, with the corresponding issues in recycling and health risks from migrating adhesives (see section 5.4).

The chosen printing type influences the type of ink can be used. For reverse printing only water-borne and solvent based inks can be used, while UV-curing and EB-curing inks can be used in surface printing too (EuPIA, 2013).

Inks types

Solvent based inks cure by drying to the air. The solvent evaporates and leaves the pigments and binders on the film. The binders make up the largest part of the ink and can be biobased resins such as nitrocellulose or rosin resin or synthetic resins such as PVB, PA, or PU. For food grade applications the former are preferred over the later due to the lower odour and migration risk. (ILSI, 2016) The evaporation of the solvents creates high risks for the release of volatile organic compounds (VOC's) which are toxic and carcinogenic. The use of mineral oils in solvents for food grade applications has been minimised (EuPIA, 2013), but contamination can happen. The migration of MOSH and MOAH need to be monitored when a solvent based ink is chosen.

Water borne inks are not 'water based' inks. The pigments and binders are still dissolved in a solvent (commonly an alcohol), but this is diluted with water. This decreases the amount of solvent that evaporates and reduces the emitted VOC's. The drawback is that the ink cures slower on non-absorbent surfaces such as plastic film. It is important to control the evaporation process because retained solvent in the dried ink can act as a plasticizer that increase the risk for migration of the ink to food and increase sett-off in surface prints (ILSI, 2016).

UV curing inks do not use solvents but a liquid binder of photo-initiators and monomers and oligomers mix with the pigments. In liquid form they can be applied to a surface. When treated with UV light, the photo-initiators start the polymerization of the monomers and oligomers, binding the pigments to the plastic film. For food safe applications be sure that highly reactive oligomers and monomers are chosen so that all are polymerized and migration is minimized. Proved safe photo-initiators with low migrating potential should be chosen, as they will remain trapped in the cured ink (ILSI, 2016).

Electron beam (EB) curing inks work in a similar way as UV curing inks, but do not require photo-initiators. Because the beams penetrate all the way into the inks, the reaction of monomers and oligomers is better controlled than that of UV curing inks. The binders and additives (with the exception of photo-initiators) are comparable to those used in UV-curing inks. Drawback of this method are currently the costs and the fact that curing must occur in a curing chamber filled with inert gas, commonly nitrogen. For both UV and EB curing applies that curing time must be tightly controlled to make sure that no unreacted oligomers and monomers are presented in partly cured inks.

Biodegradation and recycling of inks

Biodegradability of inks and varnishes is usually limited. Some biobased pigments and binders exist, so that after composting only natural occurring substances remain. But in the current industrially used inks with their required application and curing speeds minor traces of non-biodegradable additives will always remain even if the binders and pigments are biodegraded. If biodegradability is intended, print as little surface as possible.

Plastic recycling is intended to reclaim the polymers in the packaging. The addition of inks and varnishes will in any case contaminate the recycling and should be used as little as possible. Surface printing of small surfaces with a thin overcoating are preferred since reverse printed inks will require an extra lamination layer, adding to the contamination. Light colours, irrespective of curing method are preferred. The pigment TiOx (white) is a known disturbance in colouring of recyclate, while Carbon Black (black) disrupts the automatic sorting of plastic packaging waste.

Ink type	Printing types	Health risks	Environmental risks
Solvent based	Both	A summary will be made for a quick glance. No additional information will be added here.	
Water borne	Both		
UV curing	Surface printing only		
EB curing	Surface printing only		

Chemical consideration

Carefully chosen EB curing inks seem to be the most sustainable choice but can only be surface printed and require the right machinery. Surface printed inks come with health risks regarding contamination and spreading of the inks. Reverse printed inks require lamination which has its own associated health risks and consequences in recycling and biodegradation.

Pigments

Pigments are coloured, insoluble chemical compounds with the ability to give colour to another material. "Pigments keep their original shape (as small crystals) over the complete life cycle, a consideration that must be taken into account during the material health assessment process" (Cradle to Cradle Products Innovation Institute, 2019).

Pigments can be divided into two groups (Cradle to Cradle Products Innovation Institute, 2019):

1. **Inorganic pigments:** Inorganic pigments, often metal oxides or metal sulfides, usually show high light fastness and temperature stability, but often limited brilliance. Important inorganic pigments are titanium dioxide, iron oxide, zinc oxide, zinc sulfide, barium sulfate, chromium(III) oxide, cobalt blue, lead oxide, cinnabar and cadmium yellow.
2. **Organic pigments:** Similar to dyestuff molecules, organic pigments can be classified according to their chemical structure. Classes of organic pigments include: Azo pigments, Disazo pigments, Polycyclic pigments, Anthraquinone pigment, Dioxazine pigments, Triarylcarbonium pigments, Quinophthalone pigments. Azo pigments are the commercially most important group of organic pigments

Organic pigments have a superior environmental profile in comparison to inorganic pigments and provide a wider range of bright colours.

"Several toxicity studies have been performed on pigments for select hazard endpoints including acute toxicity, mutagenicity, and irritation potential. The results showed that very few pigments are hazardous. The main reason for this is that most pigments are poorly water soluble and predominantly chemically inert, and as a consequence are not bioavailable." (Cradle to Cradle Products Innovation Institute, 2019)

[More research needs to be done into the specific health and sustainability issues and risks of pigments in food packaging.]

Additives to inks

Besides the previously discussed substances in inks, a wide range of additives can be used depending on the producer, the used printing and curing techniques, the solvent, and the pigments. The ISLI lists the following possible additives in inks for food packaging (ISLI Europe, 2011):

- Acid catalysts
- Adhesion promoters
- Amine solubilisers
- Antifoam agents
- Antimist agents
- Antistatics
- Biocides
- Chelating agents
- Dispersing agents
- Flow agents
- Jellifying agents
- Inhibitors
- Ink stabilisers
- Optical brighteners
- Photoinitiators
- Plasticisers
- Siccative agents
- Slip agents
- Suspension agents
- Thickeners
- UV stabilisers
- Waxes
- Wetting agents

Inks and safe chemical selection

Regardless of the choices made about the polymer and other required chemicals, inks should always be subjected to a critical review during the design of the packaging. Involvement of the ink producer in this process is crucial. The European Printing Ink Association has published a list of excluded substances in inks (EuPIA, 2016a) and Guidelines for Good Manufacturing Practices including risk assessment and management (EuPIA, 2016b). These documents can be adhered to in the chemical selection process, besides local chemical safety regulations, food contact regulations, and a screening with the Restricted Substances List of the Cradle to Cradle Products Innovation Institute.

4. SOURCING

4.1 LAMINATION

[Needs to be further elaborated]
In this section a few lamination methods will be discussed. Extrusion lamination will not be dealt with in great detail because it is so similar (with regards to chemicals and sustainability) to coextrusion with a tie layer. The main focus is on adhesives and their constituents.

- A distinction will be made between chemical setting adhesives, specifically PU's and epoxy resins;
- and solvent-borne adhesives, specifically vinyl polymers (PVOH) and acrylic adhesives
- Solvents will be discussed: toxicity and emissions to the air from VOC's. Availability of biobased alternatives, with much lower concerns.
- Curing agents in both PU foams and epoxy resins and their migration
- The consequences at EoU will be touched upon and noted in the summarizing table, but are mainly discussed in the EoU chapter.

Adhesives	Health risks	Environmental concerns	EoU issues

Polymer consideration
Adhesive use increases the potential of migration of hazardous substances to food, increases the emissions of substances to air and soil, and decreases recycling potential. The selection of polymers that do not require adhesive lamination is preferred.

Chemical consideration
Concerns have been voiced about multiple constituents of all the discussed adhesives. When weighing the sustainability aspects for adhesive selection, priority should be given to the health concerns and migration of curing agents and solvents to the food.

4.2 GENERAL FEEDSTOCK CONSIDERATIONS

In this first paragraph the overall considerations when choosing a feedstock are discussed. Depending on the polymer(s) chosen for the packaging film, there are three main sourcing routes: primary renewable resources, primary non-renewable feedstock, or secondary feedstock (or recycled material).

Renewable resources

A resource is considered renewable when the regeneration is able to keep up with the extraction and consumption of the material. Well known examples are fast growing crops such as corn, sugarcane, sugar beet, and wheat. Rapidly renewable resources are selected to decouple feedstock extraction from fossil resources and to preserve natural capital. Using fast growing crops will also reduce the emission of greenhouse gasses (in comparison with fossil-based resources) as the growth of the plants requires them to capture CO_2 from the atmosphere. The carbon will be stored in the biomass, be converted to a plastic, and eventually will de released back into the atmosphere again as CO_2 or CH_4 (methane) when the plastic is incinerated or decomposes at end of use. A social benefit to the use of renewable resources is that, unlike reserves of fossil resources, their cultivation does not have to be concentrated in certain specific regions in the world. This means that bioplastic production can support local rural economies.

When selecting a renewable resource as feedstock for the plastic, a few other sustainability criteria should be considered: land-use change, food scarcity, and agricultural practices.
When crops are grown to serve as feedstock for plastic production, arable land is needed. The feedstock is not considered sustainable when it requires the destruction of natural capital, e.g. deforestation of rainforests to gain land. The cultivation of crops for plastic production should also not compete with food production in areas where arable land or water is scarce or crop yields are unstable. By-products or residues of food production can be selected as feedstock in these cases. Furthermore, if the cultivation of the feedstock heavily depends on fossil-based energy, through petrol for tractors and combines for instance, or on the use of fertilizers and pesticides, the overall environmental impact of the feedstock might be higher than that of fossil-based alternatives.

Not all these factors can readily be taken into account in the selection of a polymer to produce a biscuit wrapper. When a polymer derived from a renewable resource (a "bioplastic") is considered, potential suppliers and the origin of the feedstock should be checked on these criteria.

Primary non-renewable feedstock

Intuitively the fossil-based primary feedstock is regarded as least sustainable. The extraction of the feedstock is polluting and requires the destruction of natural capital. The use of the primary (or 'virgin') material means that the material cycles will not be fully closed and continual extraction of the feedstock is needed. However, the use of primary non-renewable feedstock might be required due to food safety concerns and unavailability or incompatibility of materials derived from renewable resources. In this case a plastic must be selected that can readily be recycled and the biscuit film must be designed in a way that enables the highest possible recovery of the material in the existing recycling value chain. In this way the plastic used in the biscuit wrapper can be reused in another product and replace the need for virgin plastics there.

A polymer from a primary non-renewable feedstock that cannot be readily recycled, is an unsustainable material and should not be selected for use in a short-lived product such as biscuit packaging.

Secondary feedstock

Secondary feedstock, or recycled plastics, can be derived from both renewable and non-renewable resources. The benefit of the use of secondary feedstock is that recovery of the materials after their primary use generally has less environmental and health impact than the production of virgin plastics. Additionally, the use of recycled plastic means that this material has not been discarded as waste and the impact of incineration or landfilling has been prevented. The use of recycled plastic in a new product increases the demand for recycled plastics, which makes it more likely that the plastic will be collected and recycled at end-of-use.

In food-contact applications such as biscuit packaging, the application of plastics from secondary feedstock is limited. Food safety regulations prohibit the use of plastics with risks of contamination in food-contact applications. In India for instance the use of recycled plastic is prohibited in all food contact applications. In Canada recycled plastics used in food packaging are subjected to the same regulations as virgin plastics in terms of their chemical safety. In South-Korea recycled plastic is allowed as long as it is not in direct contact with food in multilayer applications and migration of harmful substances is prevented. In the EU recycled plastic in food contact applications can only be used when the primary plastic was food grade, the collection system ensures no contamination with other material streams, and the material is recovered through a licensed recycling process.

In practice this means that only recycled PET collected through bottle deposit systems is widely adopted in food grade applications. Depending on local policy and available facilities it is possible to obtain (small quantities of) other food grade recycled plastics. For instance, when you can supply a recycler with your own separately collected food grade plastics or through a chemical recycling process. Chemical recycling will be discussed in further detail in the chapter *End-of-Use*.

Polymer consideration

In the selection of a polymer, the availability of sustainable sources needs to be considered. Sourcing has a great influence on the overall sustainability, in particular on the chosen sustainable design goals 'Close material loops' and 'Preserve natural capital'. If a polymer can only be sourced from non-renewable primary feedstock, this might not fit the goals and can no longer be regarded as a viable option.

4.3 FEEDSTOCK OPTIONS

In this paragraph the feedstock options for the potential polymers on the shortlist compiled in the *Use Phase* chapter are discussed.

Renewable resources

From the shortlist of material created in the chapter *Use phase*, the materials in table 4.1 can be derived from a renewable resource.

Polymer	Common feedstock	Availability	Remarks
BioPE	Sugar cane	Commercially available	
BioPP	Waste cooking oils and palm oil	Scarce; R&D phase	Scarce at time of writing, availability is rapidly increasing
BioPET		Small scale	Biobased feedstock is used in production, end product is ±30% biobased

PLA	Corn and sugar cane	Commercially available	
Regenerated cellulose	Wood pulp	Large commercial availability	

Table 4.1: Based on Siracusa and Blanco (2020)

BioPE, BioPP, and bioPET are so-called 'drop-in bioplastics'. They are chemically identical to PE, PP, and PET derived from fossil feedstock, have the same material properties and can be processed and recycled just as their fossil counterparts.

Polymer consideration
If renewable feedstock is preferred, currently the best options for the main polymer are BioPE, PLA, or Regenerated cellulose. When a polymer from a renewable feedstock is chosen, the potential suppliers and the origin of the feedstock should be checked to make sure that cultivation of the feedstock is sustainable in practice.

Primary non-renewable feedstock

Since biscuit wrappers are short-lived products, the selection of sustainable primary non-renewable feedstock for this purpose requires the polymer to be readily recyclable in the End-of-use phase. This means that the recycling system in the region in which the biscuits are consumed should be analysed. This will be dealt with in section 6.2 in the *End of Use* stage.

Secondary feedstock

From the shortlist of polymers created in the chapter *Use phase*, the polymers in table 4.2 can be sourced as food safe recycled plastics. Due to the current organisation of collection and sorting facilities almost all recycled plastic will have the risk of contamination with organic pollutants or non-food safe plastics. Only the separately collected PET bottles in deposit schemes are widely available for food safe recycling.

Polymer	Food safe mechanically recycled; availability	Chemically recycled
LDPE	No	No; pilot scale
HDPE	No; pilot scale	No; pilot scale
PP	No; pilot scale	Yes; small commercial scale
PET	Yes; widely available	No; pilot scale
PA	No	No; pilot scale
PLA	No	No
Regenerated cellulose	No	No

Polymer consideration
If secondary feedstock is preferred, the current available polymers are PET and PP in much lower availability from chemical recycling.

4.4 CHEMICAL ADDITIVES IN PRODUCTION OF PLASTIC RESIN

In the production of the polymers, additives are added to aid in the production of the polymer. These can be added to both the renewable and non-renewable feedstock. Residual substances might be left in the plastic from production and other substances might remain in the polymer after recycling. The health risks and sustainability of these substances is discussed in this paragraph. Only additives added by the plastic resin producer are also discussed in this chapter. Other substances that are added for purposes other than production of the polymer, such as inks for advertisement will be discussed in other chapters. Additives that are added in the production of the film are discussed in the chapter Production.

Production residues

Monomers are the starting molecules that are used to form a polymer through polymerization, or the product of degradation of a polymer after production. A well-known restricted monomer is Bisphenol A (BPA) an endocrine disrupting chemical (EDC) and a migration limit for the substance is set in EU regulation since 2018. Monomers are not expected in polyolefins as these are very volatile substances that are separated from the polymer pellets produced.

Oligomers are partially reacted monomers or degradation of polymers. They are mainly found in polyesters (PET and PLA) in food packaging applications. Oligomers can be present in polyolefins as waxes. For instance, in VLDPE's. The products are tested and only if migration stays within the accepted limits a resin is food approved.

Catalysts are chemicals that start or accelerate a chemical reaction. In this case, the polymerisation from monomers to polymers. In the production PP catalysts can be added that are formed from a 'pre-catalyst mixture' containing, among other substances, phthalates. It forms the catalyst in the reactor in which the polymerisation will take place. Phthalates such as DEHP have endocrine disrupting properties. These phthalates are usually consumed in the reactions, but traces can be left in the final PP. Most impurities are removed in the purification stage and tests are performed to determine that concentrations are below specified limits so that the material can be used in food grade substances.

Additives

Flame retardants reduce the flammability of plastics. They are not added to resin for the application in plastic film. Many flame retardants have been banned due to reprotoxicity and carcinogenic toxicity and endocrine disruption.

Heat and oxidation stabilizers are used in PP, PE, PS, PA, PET to prevent polymer degradation in extrusion. [will be elaborated upon: examples of banned or suspected stabilizers]

Clarifying agents or nucleating agents are added to improve the transparency of plastics, mainly PP. As PP is semi-crystalline these nucleating agents are the seeds to start crystallization. This leads to a product with more smaller crystals and gives better optical clarity. No food safety or environmental risks are expected with this additive.

Catalyst deactivators: used to deactivate the catalysts mentioned before. [to be elaborated]

Biocides prevent the degradation of plastics from microbiological attacks. They are not commonly used for this application. It might be used to slow down biodegradation of biodegradable plastics but for a product with such a short lifespan as packaging, refrain from using these at al.

Pigments are discussed in more detail in section 3.4, as part of the considerations regarding inks. In plastics, pigments are dispersed within a binder matrix (masterbatch), which is then added during compounding of the granules to imbue it with colour. In coloured plastics pigments are embedded in a matrix and therefore exposure is limited (Cradle to Cradle Products Innovation Institute, 2019).

Chemical consideration
Chemicals additives are added to the plastic to serve specific purposes but can have consequences for the sustainability of the plastic product. They might hamper recyclability or pose a toxicity risk to human health or biodiversity at any point in the lifecycle. It should be considered whether the addition of the chemicals to the plastic is indispensable or whether more sustainable alternatives can be chosen.

4.5 NON-INTENTIONALLY ADDED SUBSTANCES IN SECONDARY FEEDSTOCK

[will be further elaborated]

- Contaminants from previous use and the recycling process such as inks and adhesives and breakdown products from the polymer itself.
- Only mechanically recycled PET will be considered.

Chemical consideration
The selection of a polymer from a secondary feedstock has sustainable benefits as discussed on page 18 but can have its drawbacks. When considering secondary feedstock for food packaging the health risks posed by chemicals added in the recycling process or accumulated to unsafe levels should be taken into account.

5. PRODUCTION

5.1 INTRODUCTION

In this chapter the sustainability considerations with respect to chemicals used in the production of the packaging film and the filling of packaging with cookies are discussed. Production involves both the film production from the resins that are discussed in the previous chapter and multilayering of the films to form the packaging. Furthermore, it includes the filling of the packaging and the requirements and effects of the filling line. The additives that are added during compounding to aid in film production and filling are discussed in this chapter too.

Currently a lot of decisions in the production phase of the film and filling of the packaging are made based on efficiency and production speed, while staying within the allowed boundaries for food safety. In this chapter the main considerations revolve around the sustainable design goals *Guard health of participants in lifecycle* and *Close material loops*. How can the need for efficient and fast production processes be paired with safe use of chemicals? And how will it impact the recycling potential of the plastic film?

5.2 FILM PRODUCTION

Plastics films for this application are produced through casting or extrusion blowing, both with their own advantages, drawbacks, and environmental footprint. To focus on the sustainability aspects and the influence of selected chemicals, only film production additives will be discussed in this chapter.

Plasticisers are used to improve the flexibility of plastics by reducing the forces between the molecules. They are mostly used in the production of flexible PVC. Notable uses of plasticizers for the polymers on the short list are in cellulose films (Hahladakis et al, 2017) and PVdC coatings (Wang et al, 2020). Common plasticisers are phthalates, including DEHP, BBP, DBP, and DIBP which have endocrine disrupting and reprotoxic properties. For these phthalates specific migration limits are set in EU regulation. To practice safe chemical selection assume that there are no safe migration limits for these substances. Plasticisers can also be used in inks and adhesives. This is one of the reasons to use these sparingly in and on the packaging.

Polymer consideration

PVC is not on the shortlist of polymers in this case study due to the high concentration of plasticizers, suspicion of other concerning additives, and known problems in recycling. PVdC coating is used in much smaller amounts but is warned against for the same reasons. When regenerated cellulose or a polymer with PVdC coating is chosen, the use and migration of plasticisers should be investigated.

Lubricants are used to reduce the friction between processing machinery and the plastic. It improves the production efficiency, reduces energy use and wear of the machine. Lubricants are used in very small quantities.
[To be researched and described: the use of amide waxes, whether chlorinated paraffins are still relevant for this application]

Anti-block and slipping agents are used to prevent films from sticking together. They are mainly used in LDPE and PP films, and in PVC and PET to some extent (Zilles, 2014). A distinction can be made between inorganic agents, which can be compared with finely distributed mineral particles on the surface, and organic agents which can be compared to lubricants that migrate to the surface of the film. These organic anti-block agents have high migration potential since they form a release layer on the outside of the film (Zilles, 2014), in contact with the biscuits. Crystalline silica is used as an inorganic anti-block agent, this is a known carcinogen when inhaled.
[consequences of the use of anti-block agents will need to be further described.]

Oriented films

Oriented films are made by stretching casted films in one (oriented) or two (bioriented) directions. This will orient the molecules of the polymer in the direction of the stretching and consequently make the film thinner, reduce elasticity, and increase the gas and water vapor barrier (Ten Klooster, 2008). A drawback is that the film is not as easily heat sealed. This can be observed for BOPP and BOPET in table 3.1 with material properties in section 3.2. To close a packaging with this material on a fast filling line will require a sealable coating. Either through hot sealing or an adhesive. This will be discussed in further detail in section 5.6.

5.3 MULTILAYERING

Currently most biscuit wrappers and other flexible plastic packaging does not consist of a single polymer film. More common is the use of a multilayer film that combines the properties of two or more materials. Generally speaking, materials can be bonded together in three ways.
Coextrusion, in which two or more polymers melted and extruded as thin layers on top of each other.
Lamination, in which two existing films are bound together with the aid of another (liquid) material.
Coating, in which a liquid part is applied on an existing film to be bonded together.

More information for this table needs to be gathered. The method of presenting the information in this way is to be reviewed.

	PE	PP	PET	PA	PLA	Cellulose
LDPE	[illegible]					
HDPE						
PP						
BOPP						
PET				[illegible]		
BOPET						
PA			EAA tielayer			
PLA						
Cellulose						
coatings	PE	PP	PET	PA	PLA	Cellulose
Acrylics						
PVdC	EVA tielayer	tielayer				
PVOH						
EVOH						
EVA	Coex	Coex				

Table 5.1: Multilayer combinations and bonding. Bas on Falla (2016), Polymerdatabase (2020b)

Coextrusion

Regarding sustainability of the plastic film from a chemical perspective, coextrusion is likely to be preferred over lamination. Section 5.4 deals with lamination and the use of adhesives, and the sustainability aspects that are involved. When the use of adhesives can be prevented, these aspects do not need to be considered. However, the following aspects need to be taken into account when a multilayer film is coextruded.

Tielayers Coextrusion can require the extrusion of a 'tielayer' between two materials to enable two polymers to be extruded together. For example, EVA is used in the coextrusion of PA and PE. A drawback from the use of tielayers is that it require substantially more material to bond the layers than with the use of an adhesive. Extra polymer layers reduce the recycling potential of the film because there are more polymers with (slightly) different properties present in the eventual recycled product. More polymers also means more additional chemicals that need to be checked on food safety and adverse consequences at EoU.

Lubricants In coextrusion the flow behaviour of the different materials needs to be similar to prevent shear stresses between the layers (Ten Klooster, 2008). Internal lubricants can be used to finetune the compatibility of the materials. [This needs to be further investigated, likely to be linked to External Lubricants in section 5.2]

Printing. As described in section 3.4 on printing and inks, reverse printed films require a lamination in production. When reverse printing is chosen for a multilayer with two material layers, coextrusion is not an option.

Polymer consideration
Multilayers that can be coextruded are likely to be preferred over adhesive laminated multilayers due to the absence of adhesives and the consequences that come with it. But consider: • In some cases the use of tielayers needs to be considered, with their subsequent effect on material use, recycling, and food safety. • Internal lubricants are used more often. • Reverse printing requires lamination.

Coating

In the application of a food packaging film, the coating methods of dispersion coating, extrusion coating, and vapor deposition coating are relevant. Vapor deposition coating, or vacuum coating, is used to coat thin layers of metals and oxides on plastic film. It is an energy intensive process but can reduce the amount of materials used.
[Dispersion coating and extrusion coating will be further elaborated on after investigation of lamination methods. The coating methods are comparable with the lamination methods and so are their sustainability considerations. Most relevant are the solvents in the dispersion coating]

Primers: For the correct application of a coating, additional primer layers might be required. [Very little effect on overall sustainability of the packaging is expected. This might be cut later.]

Sealing: When a wax coating is chosen, this influences the possibilities for sealing, which are discussed in section 5.6. Because waxes remain heat sensitive, a cold sealing application is required (Dixon, 2011).

Chemical consideration
The use of coatings greatly reduces the material use, with the associated benefits in sourcing, recycling, and the risk of contamination. The use of primers, solvents, and waxes can have it drawback [which will be further detailed].

5.4 PRODUCT WRAPPING – PACKAGING FILLING

In the phase in which the packaging is filled, the extra added chemicals in the packaging to help in the process are dictated by the existing packaging line. In this case study the use of antistatic agents and slip agents will be discussed.

Antistatics are not commonly used in biscuit packaging. Film on a fast-moving filling line will build up static energy in the packaging. This is mainly problem with electronics packaging and the packaging of powdered goods, not biscuits. [Further reviewed and described: the use of amines and amides as antistatic agents used, with the risk of PAAs contamination. Food safe alternatives exist]

Slipping agents are used to prevent the film from sticking on the filling line and easier release from the reels. Slipping agents and the anti-blocking agents discussed in section 5.2 are comparable and can be taken into consideration in the same way.

5.5 SEALING

For the sealing of the packaging, one main choice has to be made: whether cold sealing or heat sealing is used.

Heat sealing is usually chosen in the application of a biscuit packaging because of the fast-paced filling lines. Heat sealing requires the selection of an easily heat sealable film, or a heat sealable layer on the outside (and sometimes inside) of a multilayer, or a heat sealable coating. This has been discussed in section 3.2 in table 3.1.

Cold sealing is the sealing of the packaging with an adhesive. This is uncommon in biscuit packaging but can be chosen when the requirements for heat sealing cannot be met. The selection of adhesives has been discussed in section 5.4 under Lamination. Adhesives for cold sealing will be applied selectively to allow for 'peeling' when the consumer needs to open the packaging. In the case of cold sealing, the evaporation of the solvent and the emission of by-products from the chemicals setting need to be investigated more critically. Since the product, the biscuits, are in the packaging when the adhesive is applied, uptake of the odour of the adhesive needs to be prevented.

[this will need be further elaborated, but most of it has already been mentioned in earlier stages of the life cycle]

Polymer consideration
To allow for heat sealing, the sides of the film that are sealed together must be easily heat sealable (see table 3.1 in section 3.2).

Chemical consideration
In the selection of an adhesive for cold sealing, attention must be paid to the release of odour from the adhesive in the curing to not spoil the biscuits.

6. END OF USE

6.1 END OF USE SCENARIOS

In this phase of the life cycle the biscuit packaging is discarded by the consumer. There are five End of Use (EoU) scenarios that can be considered:

- Mechanical recycling
- Chemical recycling
- Composting
- Incineration
- Landfilling

In the chemical selection for a plastic packaging it should be taken into account how the packaging will most likely be processed at End of Use. The available waste infrastructure will *steer* the choices that need to be made: the design of the packaging must fit the most sustainable option for processing at End of Use. This includes the collection and sorting that are required before any of the aforementioned processes. In case of recycling, the material must be able to be recovered in the best possible quality to be reused in a new product. In all scenario's, exposure of waste management workers to hazardous chemicals or emissions of hazardous substances to the environment must be prevented. Emissions of greenhouse gasses should be limited.

Littering

Littering of plastic packaging has detrimental effect on the environment but is not considered as an EoU scenario in this case study. Small plastic films for single serving food items such a candy bars are among the most littered plastic items but multi-packaging for collated biscuits is rarely littered.

Polymer consideration
In the selection of a polymer the End of Use options should be considered. For the chosen sustainable design goal 'Close material loops' the recyclability or compostability of the material is key.

In figure 6.1 the possible EoU scenarios of the plastic biscuit packaging are shown. Green arrow show the most sustainable routes: the possibilities are however decided by availability of the facilities and design of the packaging.

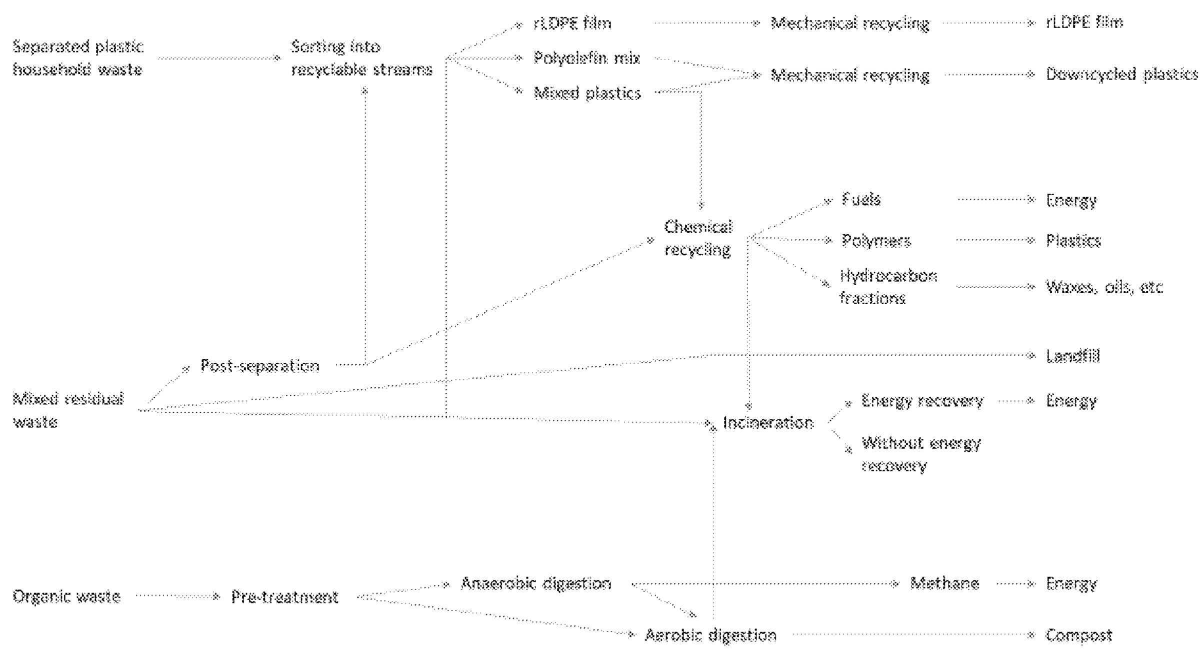


Figure 6.1: The different End of Use scenarios. The green arrows depict the most sustainable route per step in the scenario, depending on the available facilities and design choices that are made.

6.2 WASTE COLLECTION

When discarded properly by the consumer, the packaging film can be collected through four main routes. Which one, depends mostly on local availability of the collection system and on the composition of the plastic film.

Residual waste

Currently the most common route of collection is the municipal waste collection of residual household waste. The plastic film is be mixed with food scraps and other unsorted materials. It might be sorted-out for recycling in a so-called post-separation plant, also sometimes called a post-collection separation plant. Unsorted residual waste is either incinerated or landfilled.

Separated plastic packaging waste

If available, the packaging film can be discarded by the consumer through the separate collection of plastic packaging waste, pre-sorted from the residual waste by the consumer at home. Plastic packaging film is not in all countries collected in these systems. Multi-material plastic films such as combinations of plastic and aluminium or plastic and paper are not (yet) collected in these systems. After collection it needs to be sorted in one of the material streams for further recycling. It is highly recommended that recyclability of the packaging is indicated on the packaging. If the packaging is recyclable the consumer should be reminded to properly discard it with the recyclable plastic waste. If the packaging cannot be recycled in the available facilities, the consumer should be informed to prevent improper disposal and contamination of the recycling stream.

Organic waste collection

If separate collection or organic waste is available and the plastic film can be (industrially) composted, the film can be collected through this service. This should again be indicated on the packaging, preferably in a very obvious way. Compostable plastics

Post-separation

Recent technological developments allow for separation plastic packaging waste from mixed residual waste in post-(collection-)separation facilities. Availability of these sorting facilities is not widespread at the time of writing (late 2020). After sorting, the separated plastic will be transferred to plastic recycling plants or might be sorted a second time in plastic sorting facilities into different polymer streams.

6.3 SORTING

Sorting for mechanical recycling

Plastics that are either pre-separated in households or separated from the residual waste after collection, will need to be sorted in a few main polymer 'streams' before they are fit for recycling. The sorted and recycled streams vary per country. Usually rigid PET, HPDE and sometimes PP are sorted as individual streams. Plastic films are separated from the rest with a windsifter and are either sorted as one residual stream of mixed films, or further sorted with a near-infrared spectroscopy. LDPE is the main polymer used to make plastic films; PP is very common. When films are further sorted, a monostream of LDPE can be sorted out to be recycled into LDPE films again. This does currently require the film to have a larger surface area than the biscuit packaging film. A mixed fraction of polyolefins (PE and PP) can also be sorted from the other films, with the other films being diverted to incineration. Both the polyolefin mix stream and the unsorted mix stream of plastic films are recycled into thick walled low-grade products. All none-polyolefin substances in the material mix are contaminations to the stream and will decrease the quality of the recycled material and consequently increase the required material use and production waste.

Polymer consideration

To enable sorting for mechanical recycling, the film should contain a high percentage of polyolefins. To allow for NIR sorting, the outside layer of a multilayer should be a PE or PP. Due to its size the film will in any case be sorted in the fraction of mixed films or mixed plastic and be downcycled in a low-grade plastic.

Sorting for organic waste treatment

Collected organic waste is usually not sorted but pre-treated in the organic waste treatment facility (industrially composting facility). It will be shredded to smaller bits to increase the total surface area of the particles and then sieved. In this process the collected waste will be checked for contaminations, for instance with non-compostable plastic, which is sorted out manually but not consistently. The compostable plastic film should be clearly recognizable as (industrially) compostable by the facility's staff to be left in the organic and not sorted out and diverted to incineration. This can be achieved by printing multiple large markings for compostable material such as the 'OK Compost' or 'seedling' logos on the packaging.

6.4 MECHANICAL RECYCLING

As discussed under Sorting, if the mechanical recycling scenario is chosen, the current sorting facilities for plastic packaging will sort the biscuit packaging film in a fraction of mixed plastics or in a fraction of mixed polyolefin (PO) films. This is due to the size of the film, regardless of the chemical composition. To allow for the highest possible recycling of these streams, the film should (CEFLEX, 2020):

- be minimal 90% mono-PP, mono-PE layers, or mixed PO layers by mass;
- not contain PVC, PVdC, PET, biodegradable material, or foamed polymers other than PO's (CEFLEX, 2020);
- not contain aluminium, oxo-degradable plastics, or paper (KIDV,2019).

If these requirements are not met the packaging film contaminate the fraction, decreasing the efficiency of the recycling process. This could for instance lead to more blockage in the melt filters when the shredded material is remelted to pellets, which in turn leads to the wastage of other recyclable material. When it ends up in recycled material it will decrease the quality of the plastic, which increases the production waste and required material for new products made with recycled plastics.

Chemical consideration
To enable efficient mechanical recycling, the film should be made from mono- PE or PP layers or at least a multilayer containing 90% percentage of polyolefins. It should not contain PVC, PVdC, PET, oxo-degradable plastics, biodegradable plastics, foamed non-polyolefin plastics, aluminium, or paper. Other barrier layers or chemical additives are contaminants to the recycled and should combined not exceed 10% of the film's mass.

Health risks in mechanical recycling

- The exposures of staff members in recycling facilities to emitted substances in the mechanical reprocessing of polymers. Both the polymers and additives need to be listed in a 'risk watch list'.
- The same goes for the health risk of the compounding of the substances in the application of recycled plastics in new products. In this case it will be assumed that the recyclate will not be used in food-grade applications.

[This table is currently incomplete]

Polymers	Health risk in recycling	Health risk in recyclate
PE	Butane in fume	
PP	Formaldehyde, acrolein, acetone in fume	
PET	Formaldehyde in fume	Formaldehyde and acetyldehyde as thermal degradation products.
PA		
PLA		
Regenerated cellulose		
Coatings	Health risk in recycling	Health risk in recyclate

Acrylics		
PVdC	Hydrogen chloride in fume	
PVOH		
EVOH		
EVA		
Notable additives	Health risk in recycling	Health risk in recyclate
Inks		
Adhesives		
Pigments		

Chemical consideration

If mechanical recycling is seen as a plausible EoU scenario for the packaging, the health risks in the process and risks posed in the recycled material should be considered in the polymer and chemicals selection.

Environmental risks in mechanical recycling

- Thermal degradation and abrasion of the polymers will lead to microplastics and a number of chemical degradation products that will be included in the table above.
- The products made from the recyclate will most likely be 'downcycled' plastic products: public benches, road side marker posts, riverbed bulkhead. Used outside, it will shed microplastics and leach it chemicals into the environment.
- To minimize environmental risks like these, the impurities in the recyclate should be kept to a minimum; i.e. minimize everything that is not a polyolefin polymer.

6.5 CHEMICAL RECYCLING

- Chemical recycling is a promising solution for the recycling of plastic films. However, there are still technical difficulties and currently the environmental benefits are small (weighing CO_2 emissions and energy use against material circularity)
- A distinction can be made between chemical recycling to new plastics, to lower grade oil products, and to fuel.
- Waste-to-fuel or chemical downcycling should not be regarded as sustainable solutions in the long run.
- Chemical recycling technologies are in theory able to process a mix of plastics and polluted plastic waste. However, the chemical recycling back to plastics is a selective process in which a specific polymer is reclaimed. All other contaminations in the throughput reduce the efficiency of the process. The films should contain as much of one of these specific polymers as possible.
- Chemical recycling is not available on a scale that it should be taken in considerations in current designs. The availability of chemical recycled plastics comes from pilot plants and waste that is collected in specific areas.

Polymer consideration

If chemical recycling is seen as a plausible EoU scenario for the packaging, the packaging should contain as much of the specific targeted polymers as possible. For now, those are PET or polyolefins.

6.6 COMPOSTING

- Composting is an EoU scenario that is possible for only few of the shortlisted polymers. The addition of other layers, inks, and chemical additives will have a negative influence on the biodegradation.
- There are options to make a fully compostable film for biscuits packaging when a list of design guidelines is adhered to. This will have consequences in the Use phase and Production phase of the life cycle.

Polymer and chemical consideration
If composting is seen a desired EoU scenario for the packaging, the main polymer and the barrier layers should be compostable but biodegradability of the additives should also be considered. Substances such as inks and adhesives require extra attention because of the amounts in which they are used.

6.7 INCINERATION AND LANDFILLING

Incineration of plastics in general releases many hazardous substances in the environment. Incomplete combustion of plastic in general emits "Volatile organic compounds (VOCs), semi- VOCs, smoke (particulate matter), particulate bound heavy metals, polycyclic aromatic hydrocarbons (PAH's), polychlorinated dibenzofurans (PCDF's) and dioxins" (Verma, Vinoda, Papireddy, & Gowda, 2016).

[A general description of the consequences of plastics and plastic degradation in landfills will be made, including:]

- Capacity of landfills is finite: landfilling is not an activity that can be sustained over time. (Defra et al., 2006)
- Landfills are leaking: to the soil and marine environment
- Wildlife ingesting plastics or getting entangled in plastic waste
- Creation of microplastics
- Leakage of additive chemicals to the environment and transfer of these chemicals to animals and humans
- Over time, plastic degrades and decomposes over hundreds or thousands of years fragmenting into microplastics and nanoplastics.

In the table below notable risks for specific polymer, coatings, and additives are listed. The health risks for waste facility staff is listed, as is specific environmental risk per material. Long term risks for human health from landfilling are included in the Environmental risks of landfilling.

[This table is currently incomplete]

Polymers	Health risk in incineration	Environmental risk in incineration	Environmental risk of landfilling
PE			
PP			
PET			
PA			
PLA			

Regenerated cellulose	Release of DEHP, when used as plasticiser		
Coatings	Health risk in incineration	Environmental risk in incineration	Environmental risk of landfilling
Acrylics			
PVdC	Release of HCl, release of DEHP, when used as plasticiser		
PVOH			
EVOH	Low risk		
EVA			
Notable additives	Health risk in incineration	Environmental risk in incineration	Environmental risk of landfilling
Inks			
Adhesives			
Pigments			

Chemical consideration
If incineration or landfilling are seen as a plausible EoU scenarios for the packaging, the health risks associated with the incineration or degradation of the polymers and chemicals should be taken into consideration.

7. KEY CONSIDERATIONS & TRADE-OFFS

7.1 KEY CONSIDERATIONS

Key considerations are the most important sustainability aspects to base a material selection on. For a biscuit wrapper, the following hotspots are identified per life cycle stage

Sourcing

- The availability of sustainably cultivated renewable feedstock or food-safe secondary feedstock, or the use primary non-renewable feedstock.

Production

- The risk of hazardous substances used in the production of the resin or the film that are left in the packaging and the consumer might get in contact with.
- Whether the use of adhesive lamination might be prevented, preventing extra risks in emissions and migration, and increasing recyclability.

Use phase

- The material or combination of materials that meet the required functional properties: vapor barrier, heat sealable, and tear resistant.

End of Use

- The recycling potential or compostability of the material or material combination.
- The health and environmental risk in waste management of the degradation or incineration of the material.

7.2 TRADE-OFFS

The decisions or constraints in one step of the life cycle influence the possibilities in the other stages. The table below indicates how constraints set in the top row of the table influence the stages in the most left column.

How → influences ↓	Sourcing	Production	Use	End of Use
Sourcing		The selected method of film production requires the use of specific additives.	Requirements on food safety and barrier properties, limit sourcing options.	Preferred EoU scenario limits the amount of possible materials.
Production	Available materials might require specific production methods and additives.		Barrier properties require bonding of multiple materials.	Recycling or composting preference limits the use of laminated films and the used additives

Use	Properties of the available materials might not meet requirements.	The production method requires additives that might migrate to the food.		Preferred EoU scenario limits the use of combined materials with optimal properties.
End of Use	Selected polymers and their required additives might limit the EoU options.	Lamination of the materials decreases the recyclability and compostability.	Required barrier properties lead to materials with low recycling potential.	

Food safety and safety of the staff in the waste management is a constraint that should not be sacrificed on. The main trade-offs that need to be made are choices regarding the material properties and the shelf life of the product versus the sustainable sourcing of the material and the recycling potential. Below the main trade-offs are listed. Three times a choice has to be made between an option on the left and an option on the right. Below the two options the corresponding Sustainable Design Goal is written. In this way a trade-off between the goals can be made, and the implications on the design of the packaging can be weighed.

Either the packaging is optimized for recycling by using monolayer film, but this decreases the barrier properties and the biscuits have a shorter lifespan.	or	The biscuits are preserved longer but the recycling potential of the packaging is decreased.
Close material loops	*vs*	*Prevent product spoilage*

Renewable feedstock is selected, but the barrier properties decrease and the biscuits have a shorter lifespan.	or	The biscuits are preserved longer, but a non-renewable primary feedstock is selected.
Preserve natural capital	*vs*	*Prevent product spoilage*

The same barrier requirements are met with a monolayer film, but more materials need to be used.	or	Materials are combined and less material is used, but the recycling potential of the packaging decreases.
Close material loops	*vs*	*Reduce material use*

8. MATERIAL ASSESSMENT

8.1 MATERIAL CHOICE MATRIX

In this chapter an example of a material choice matrix is given. The shortlist of material options is checked with the sustainability criteria regarding the polymer selection. This will be done in a colour coded table to get a quick overview of the differences between the materials. To the criteria comparable, make sure that the cells have comparable sizes. More important criteria can be given bigger cells are fat printed number to indicate their importance. In the horizontal top row of the table the polymers and the coatings will be listed. In this way, combinations of materials can be judged.

	LDPE	HDPE	PP	BOPP	PET	BOPET	PA	PLA	Regenerated cellulose	Acrylics	PVdC	PVOH	EVOH	EVA
Vapor barrier	**2**	**3**	**2**	**3**	**2**	**2**	**1**	**1**	**1**	**1**	**4**	**1**	**1**	**1**
Heat sealable	3	3	3	1	1	1	1	2	1	3	1	3	2	3
Tear resistant	2	3	3	4	4	4	4	2	3	1	1	1	1	3
Renewable feedstock	3	1	2	2	2	2	1	4	4	1	1	1	1	1
Secondary feedstock	1	1	2	2	4	3	1	1	1	1	1	1	1	1
Little risk of hazardous prod. additives	**3**	**4**	**3**	**3**	**3**	**3**	**2**	**3**	**2**	**2**	**2**	**3**	**3**	**3**
Adhesive lamination can be prevented	Further review of this criterium and a method for judgement is needed.													
Compostable	1	1	1	1	1	1	1	3	4	1	1	3	2	2
Recyclable	**4**	**3**	**3**	**3**	**2**	**2**	**1**	**2**	**2**	**2**	**1**	**2**	**2**	**2**
Few health and environmental risks in recycling	**3**	**3**	**3**	**3**	**3**	**3**	**2**	**2**	**2**	**2**	**1**	**3**	**3**	**3**
Few extra risks in landfill or incineration	2	2	2	2	2	2	2	3	4	2	2	4	2	2

[The judgements made in this choice matrix are under review and not definitive.]

8.2 CHEMICAL CONSIDERATIONS

When a polymer or a combination of polymers is chosen, the relevant chemical considerations need to be revisited to make decisions in the production process and for a safe and sustainable chemical selection. During the analysis of the life cycle, these considerations have been encountered.

Feedstock selection

- When considering secondary feedstock for food packaging the health risks posed by chemicals added in the recycling process or accumulated to unsafe levels should be taken into account.
- When a polymer from a renewable feedstock is chosen, the potential suppliers and the origin of the feedstock should be checked to make sure that cultivation of the feedstock is sustainable in practice.

Plastic and film production

- Residual production chemicals might be left in the packaging. Check with your supplier what the risks are and perform relevant migration tests.
- Multilayers that can be coextruded are likely to be preferred over adhesive laminated multilayers due to the absence of adhesives and the consequences that come with it. Investigate the effect of tielayers and lubricants.
- The use of coatings greatly reduces the material use, with the associated benefits in sourcing, recycling, and the risk of contamination. The use of primers, solvents, and waxes can drawbacks.

Adhesives

- When weighing the sustainability aspects for adhesive selection, priority should be given to the health concerns and migration of curing agents and solvents to the food.
- In the selection of an adhesive for cold sealing, attention must be paid to the release of odour from the adhesive in the curing to not spoil the biscuits.

Printing

- Carefully chosen EB curing inks seem to be the most sustainable choice but can only be surface printed and required the right machinery. Surface printed inks come with health risks regarding contamination and spreading of the inks. Reverse printed inks require lamination which has its own associated health risks and consequences in recycling and biodegradation.

End of Use

- To enable efficient mechanical recycling, the film should be made from mono- PE or PP layers or at least a multilayer containing 90% percentage of polyolefins. It should not contain PVC, PVdC, PET, oxo-degradable plastics, biodegradable plastics, foamed non-polyolefin plastics, aluminium, or paper. Other barrier layers or chemical additives are contaminants to the recycled and should combined not exceed 10% of the film's mass.
- If composting is seen a desired EoU scenario for the packaging, the main polymer and the barrier layers should be compostable but biodegradability of the additives should also be considered. Substances such as inks and adhesives require extra attention.
- If incineration or landfilling are seen as a plausible EoU scenarios for the packaging, the health risks associated with the incineration or degradation of the polymers and chemicals should be taken into consideration.

[This will need to be further elaborated when further research into production additives and adhesives lead to more considerations]

For a safe chemical selection the next steps will need to be taken:

1. Check, in collaboration with your material supplier if necessary, whether the found chemical considerations involve any of the substances on the Restricted Substances List (RSL) of the Cradle to Cradle Products Innovation Institute.
2. If substances on the RSL are part of a chemical consideration, try to find an alternative substance for the intended goal.
3. If no alternative is possible, verify that the concentration of the substance is below the limit set in the RSL.
4. If incorporation of substances on the RSL is inevitable for the product, verify through relevant migration tests that these substances do not migrate into the food at all.
5. If steps 3 or 4 cannot be passed, revisit the material choice matrix and select another material or material combination.

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